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X-RAY PROPERTIES OF THE Be/X-RAY SYSTEM 2S0114+650 = LSI+65^{o}010

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ABSTRACT

Results are presented from experiments on the Einstein Observatory, HEAO-1 and OSO-8 on the temporal and spectral properties of 2S0114+650. In a 12 hour Einstein MPC and SSS observation two episodes of flaring occurred by an order of magnitude over about 1 hour. Variability on shorter time scales showed a preferred period of 14.9 minutes, but periodic pulsations were not seen in the HEAO-1 and OSO-8 data. The spectra above 1 keV were typical of accreting X-ray pulsars, a power law $E^{-\alpha}$ with $\alpha \sim 1.2$ for the number spectrum up to a cut-off at $\sim$ 14 keV. There is some evidence that the spectrum is steeper when the source is quiescent at low luminosity, but no large spectral changes attended the flares. Absorption column densities were consistent with interstellar reddening of the proposed companion, the Be star LSI+65^{o}010. In the minute and hour variability and in the spectral character, 2S0114+650 is similar to other Be star-neutron star binary X-ray sources. Variations over several days in the OSO-8 data suggest orbital effects.

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I. INTRODUCTION

There is a class of low luminosity (10^{33}-10^{35} erg s^{-1}) 2-10 keV X-ray sources associated with main sequence Be stars (Bradt et al. 1977; Maraschi, Treves, and van den Heuvel 1976; Rappaport and van den Heuvel 1981). Stable X-ray pulsations have been detected from many of these systems and long term measurements of these pulsation periods have indicated that the X-ray pulsars must be in orbits about the Be stars with periods of order tens to hundreds of days (McClintock et al. 1977; White et al. 1978; Li et al. 1979; White et al. 1982). Evidence for such a period has been obtained only for the transient X-ray source 4U0115+63 (Rappaport et al. 1978). Periodic outbursts from some of these systems also suggest similar orbital periods (e.g. Watson, Warwick and Ricketts 1981). Secular changes in the periods of the pulsars, mass loss considerations, and the peak luminosities seen from the transients indicate that the pulsars are accreting neutron stars (White, Mason and Sanford 1976; Rappaport et al. 1978; Rappaport and van den Heuvel 1981; White et al. 1982). Correlated evolution of the pulse periods and the companion mass loss has been speculated (van den Heuvel 1977; Ghosh and Lamb 1978). The range of binary conditions imply a range of accretion rates that may influence the beaming and spectra of the pulsars (Rappaport and Joss 1977; White, Swank and Holt 1983). Rappaport and van den Heuvel (1981) have suggested on evolutionary grounds that neutron star binaries with Be star companions are likely to have longer periods than those with OB supergiant companions. Thus the properties of sources of this type have a bearing on several interesting questions.

The X-ray source 2S0114+650 was first reported in the SAS-3 galactic survey by Dower and Kelly (1977). Its optical counterpart, identified by Margon (1977) as LSI+65^{o}010 (Hardorp et al. 1959), is an 11th magnitude

B0.5III star which presents a broad Hα emission line in its spectrum (Margon 1980). There are two other hard X-ray sources associated with dwarf Be stars within 3^{0} of 2S0114+650: γ Cas (MX0053+64) and the recurrent transient 4U0115+63 (Bradt, Doxsey and Jenigan 1979). The distance estimates for γ Cas of 300 pc (Moffat et al. 1973); for 2S0115+634 of 3.5 kpc (Rappaport et al. 1978); and for 2S0114+650 of 1.4 kpc (Margon 1980) put γ Cas in the local Orion arm and the other two in opposite sides of the Perseus spiral arm (e.g. Humphreys 1979). Their proximity in the sky reflects a high probability of finding Be stars in regions dense in early type stars. A similar clustering of X-ray binaries with early companions is found in Centaurus where we view along the Carina spiral arm (White et al. 1980). While the X-ray properties of γ Cas and 4U0115+63 are now reasonably well studied (e.g. White et al. 1982; Rose et al. 1980) those of 2S0114+650 are not. In this paper we report the spectral and temporal properties of this source and find them to be very similar to other members of this class.

II. OBSERVATIONS AND RESULTS

2S0114+650 was observed by the Einstein Observatory on 1979 Jan 17 for a duration of 12 hours with the Solid State Spectrometer (SSS; 0.5-4.5 keV) and the Monitor Proportional Counter (MPC; 1.5-10 keV). Descriptions of these instruments were given by Joyce et al. (1978) and Giacconi et al. (1979). The mean observed flux in the 1.5-10 keV energy band was 7 MPC cts s^{-1}, corresponding to $\sim 2 \times 10^{-10}$ erg $cm^{-2}s^{-1}$ and, assuming a distance of 1.4 kpc, a luminosity of $\sim 4 \times 10^{34}$ ergs s^{-1}. The HEAO-1 A2 experiment (see Rothschild et al. 1979) scans during 11-17 August 1978 detected 2S0114+650 at a flux level down by a factor of 5 with respect to the MPC observation. Twenty-two days earlier, on July 20, 1978, a 6 hour pointed observation of the 3.6 s transient X-ray pulsar 4U0115+63 was made (cf. Rose et al. 1979). Although

4U0115+63 was the target, no X-ray pulsations at 3.6 s were detected, and 2S0114+650 probably provided the counts we detected. The 2-60 keV "A" detector of the Goddard Cosmic X-ray Spectroscopy Experiment on OSO-8 (Serlemitsos et al. 1976) scanned the source during 27 Jan.-1 Feb. 1976. Again the response during the scans indicated that 4U0115+63 was not detected during the observation.

a. Temporal Behavior

Figure 1 is a plot of the MPC 2.56 s rates data binned so that each value corresponds to 40.96 seconds. Two prominent outbursts are evident. In each case there is an increase in flux by a factor of 3 above the mean and lasting for ~ 1 hr. This represents a range in 2-10 keV X-ray luminosities of $L_X \sim 4 \times 10^{33} - 6 \times 10^{34}$ ergs s^{-1}. There is also variability on timescales of minutes. Figure 2 is a power spectrum computed from the MPC 2.56s rates and shows considerable noise at low frequencies that reflects the flaring activity. On top of this there is evidence for significant power at 14.9 min No other significant pulsations were found for shorter periods, with upper limits of 9% down to 11. seconds, 17% for 11. - 0.04s and 22% for 0.04 - 0.004 s (Weisskopf and Leaky, private communication.)

In Figure 3 we have plotted four portions of the 3-10 keV MPC data folded on the 14.9 min period using in each case the same initial epoch. The four plots are a) first outburst region, b) second outburst, c) prior to first outburst, d) between outbursts. (These intervals are indicated in Figure 1). Although the amplitudes, mean intensities and shapes of the pulses vary (as would be expected from the raw data), all four curves peak between phases 0.3 and 0.5 and have a minimum around phase 0.7, indicating rough coherence in the pulses over the whole data set. The expected positions of pulse maxima in the raw data, based on the profiles in Figure 3a, are marked

in Figure 1. Most of the pulses are visible, although their varying structure is apparent, especially in those cases in which there are multiple peaks within a period. Figure 4(a) shows the pulse profile of 2S0114+650 obtained by folding all the MPC data with the 14.9 minute period, while Figure 4(b) is the hardness ratio defined as flux (3-10 keV)/flux(1.5-3 keV). As in X Per (White et al. 1982) there is a hardening of the spectrum during decline that ends at pulse minimum. Note however, the hardness ratio in 2S0114+650 is ~ 3 times larger than that in X Per corresponding to a flatter spectrum, $\alpha \sim 1.2$ versus ~ 2 for X-Per in a power law model, as we discuss below. The peak-to-mean amplitudes for the energy bands 0.5-4.5, 1.5-3.0 keV and 3-10 keV are 20%, 26% and 21%, respectively.

The OSO-8 and HEAO-1 scanning observations, each covering 6 days, are shown in Figure 5. Variability on timescales of several days can be seen, especially in the OSO-8 light curve where a transition from maximum to minimum occurs over ~ 4 days and represents a factor of ~ 10 decrease in flux. There is evidence for more rapid variability which is probably similar to the flaring activity observed in the Einstein observations (Figure 1). During the ~ 1 day interval Jan 31, 1975 (≡ JD 2,443,808.5 in Figure 4) the source was undetectable with a 3σ upper limit of $\sim 2.1 \times 10^{-11}$ ergs cm^{-2} s^{-1}.

Figure 6 shows the light curve for the 6^h HEAO-1 point, assuming 4U0115+63 was not contributing. The average flux implied is the same as that during the scanning observations and during the low portions of the Einstein MPC data. There is no evidence in the data for pulsations at ~ 3.6 s, the pulse period of 4U0115+63, although the upper limit of 30% is not very restrictive. Variations of a factor of 2 with time scales of 10-30 min are evident. But there is also no evidence for pulsations at 14.9 minutes greater than ~ 20%, compared to the level of ~ 25% seen in the MPC data. We were also

unable to confirm the pulsations in the OSO-8 data for which the flux was high, although our upper limit of ~ 25% is comparable to the observed MPC modulation.

b. Spectrum

Spectral data indicate that for all the observations the 2-10 keV spectrum was hard, similar to that from other members of this class (Becker et al. 1979; White et al. 1982; White, Swank and Holt 1983). Table 1 shows the fits for the absorbed power law and thermal bremsstrahlung models that fit both the MPC 2-10 keV data and the SSS 1.3-4.5 keV data. There was no significant difference between the spectra of the flares and of the low states during the Einstein observation. However, the spectrum during the HEAO-1 A2 point, when the source was weaker, appears to be slightly steeper. Figure 7 shows inferred spectra from these observations for the data above 1.3 keV. The OSO-8 data (from the early part of the observation, when the source was bright) are only shown above 10 keV. Below this there was some contribution to the OSO-8 pulse height data from the Tycho supernova remnant, which has a (2-10 keV) spectrum softer than the spectrum of 2S0114+650 seen during the Einstein observation (Pravdo et al. 1979). We deduce from the observed spectrum that the high state power law for 2S0114+650 has a cutoff at least above ~ 15 keV.

The column densities obtained in the proportional counter fits are $\sim 3 \cdot 10^{22}$ cm^{-2} and are consistant, within 3σ, with the reddening of LSI+65^{o}010. Margon (1977) reports B-V ~ 1.18, which would imply column densities $\sim 10^{22}$ cm^{-2} (Gorenstein 1975). Because of source confusion in the low energy OSO-8 pulse height data, we cannot determine whether there is any evidence for absorption increases that might attend a possible eclipse transition prior to Jan. 31, 1975, when the source was below the OSO-8 detection limit. However,

there is no strong indication of enhanced absorption during the HEAO-1 A2 observation, when again the source was weak.

There is some discrepancy in Figure 7 between the lowest energy (1-3 keV) SSS and MPC estimates of the incident spectra. This is due to the strong model-dependence of the lowest energy MPC points (channel 1). Also, the SSS spectra are affected by an excess below 1 keV. Because of uncertainties in the background subtraction needed for this observation, it is difficult to determine the properties of this soft excess. However, if it is assumed to be emission from the primary itself then it corresponds to an $L_X \sim 10^{33}$ ergs s^{-1} with a temperature of $\sim 10^6$ K. This is more than three orders of magnitude larger than that expected from a dwarf B star (Pallavicini et al. 1981).

III. DISCUSSION

The X-ray spectrum and time variability of 2S0114+650 are very similar to other members of the X Per class of Be stars. Two outbursts, seperated by ~ 6 hours, and representing an order of magnitude variation in luminosity, were resolved during the 12-hour Einstein Observation. In its flaring activity, 2S0114+650 is similar to X Per where outbursts lasting about 1 hour have been known to occur at ~ 11 hour intervals (White et al. 1976). From the OSO-8 observation of 2S0114+650 we see that the frequency and/or amplitude of flaring varies on longer time scales (1-2 days), which may be related to orbital phase. Also, the flux can remain below 1 μJy for as long as a day. While this might suggest an eclipse, similiarly low flux levels were also seen for several hours during the Einstein observation and the HEAO-1 point. Even at this low level variations occur which suggest the compact object is still in view as the X-ray source. Also, the spectrum is not significantly more absorbed at any time as would be expected for a grazing eclipse by a star with an extended atmosphere. Thus it seems unlikely that the low observed in the

OSO-8 data is due to an eclipse.

Limits on possible binary periods for 2S0114+650 can be made by assuming that its X-ray luminosity is a result of spherical accretion from the stellar wind of the primary as described by Davidson and Ostriker (1973). The gravitational energy released by the accreted material, the accretion radius, the velocity of the wind, and Kepler's third law give the following relation for the orbital period

$$P(\mathrm{day}) = 140 \quad \zeta^{3/4} \dot{M}_{-8}^{3/4} L_{33}^{-3/4} \left(\frac{R_X}{10\mathrm{km}}\right)^{-3/4} \left(\frac{M_X}{M_\odot}\right)^{9/4} v_3^{-3} \left(\frac{M_T}{M_\odot}\right)^{-1/2}$$

where ζ is an efficiency factor for the conversion of gravitational potential energy into the observed radiation, $\dot{M}_{-8}$ is the primary's mass-loss rate in 10^{-8} $M_\odot$ yr^{-1} (assumed spherically symmetric), L_{33} is the X-ray luminosity in units of 10^{33} ergs s^{-1}, R_X and M_X are the radius and mass of the compact object, respectively, v_3 is the wind velocity in units of 10^3 km s^{-1} and M_T is the total mass of the binary system. A crude estimate of v_3 can be infered from the width of the Hα emission line if it is assumed that the emission is produced in the radially expanding wind of the Be star. From the first profile in Margon's (1980) Figure 3 we estimate $\Delta\lambda \lesssim 42$ Å which implies $v_3 \lesssim 0.9$. (This could be an overestimate if the Hα-emission region is much larger than the radius of the orbit). Typical values for the wind velocities in X Per and γ Cas lie between 500 and 1000 km/s with mass-loss rates between 10^{-8} and 10^{-11} $M_\odot$ yr^{-1} (Hammerschlag-Hensberge et al. 1980; Snow 1981).

Using $M_T = 15$ $M_\odot$, $M_X = 1.4$ $M_\odot$, $v_3 \sim 0.9$, $L_{33} = 10$, $R_X = 10$ km for $\dot{M} = 10^{-11} - 10^{-8}$ $M_\odot$ yr^{-1}, we obtain possible orbital periods in the range $\sim (0.07 - 18)$ $\zeta^{3/4}$ day. If $\zeta \sim 0.1$, only orbital periods $\lesssim 3$ d could give sufficient

X-ray luminosity, in contrast to the long periods (>15 d) indicated for other Be star systems. Longer periods would be consistent if $v_3 < 0.9$, $\dot{M} > 10^{-8}\ M_0\ y^{-1}$, or the mass loss is concentrated in the orbital plane. A similar problem was encountered by White et al. (1982) in their calculation of the mass-loss rates required to power the observed X-ray luminosities in X Per and γ Cas. The variations in luminosity in 2S0114+650 on timescales of days may either reflect changes in the mass loss rate from the star, an eccentric orbit for the neutron star, or a misalignment between the orbital plane and the equatorial plane of the rotating Be star.

The Einstein data exhibit a preferred period of 14.9 minutes for the short term variability with the pulsations maintaining coherence over the 44 cycles contained in the observation. This period is close to that of the 13.9 min period of the prototype X Per. We were not able to confirm periodicity in the other data although the limits on pulsations were not very restrictive. This periodicity is reminiscent of another Be star X-ray source with a neutron star companion, γ Cas. White et al. (1982) report variations which look like pulses and appear coherent over short intervals but over multiple observing intervals change period. They suggest that these variations result from inhomogenities in the wind.

The spectrum of 2S0114+650 is similar, as measured by the MPC and SSS, to typical pulsar spectra above 1 keV (White, Swank and Holt 1982). The cutoff at $\gtrsim$ 15.6 keV indicated by OSO-8 when the spectrum is flat is also typical. For example, 4U1145-61 and 4U1538-52 exhibit cutoffs at ~ 16 keV. Although the power law index derived from the Einstein and OSO-8 data is somewhat smaller than those of X-Per and γ Cas, the HEAO A2 spectrum would be typical of the latter. The long term change between the Einstein and HEAO A2 observation is the first marked spectral change reported for these systems.

The lack of spectral correlation with relatively short time-scale flares (15 min) exhibited in the Einstein data is also typical of the behaviors of X-Per and γ Cas (White et al. 1982). While on the basis of γ Cas, X-Per, 4U1145-61, and 4U1538-52 it would be tempting to conclude that the steepness of the power law reflects the much lower luminosities of γ Cas and X-Per, 2S0114+650 provides a counter-example. Indeed the observations suggest the power law for low luminosity states is not unique.

IV. CONCLUSIONS

We have shown that 2S0114+650 shares several characteristics with other members of the Be/X-ray class. In particular, its temporal behavior is analogous to that of X-Per and γ Cas, although its spectrum is somewhat flatter. The variability on 14.9 minutes timescale in the Einstein data suggests the possibility that 2S0114+650 contains a pulsar, as in the case of X-Per. However, further observations are needed to determine whether this period persists over longer timescales.

If the binary period is $\gtrsim$ 15 days, as is suggested by other Be/X-ray sources, then mass-loss rates $\gtrsim 10^{-8}$ $M_{\odot}$ yr^{-1} or material concentrated in the orbital plane are required to produce the observed X-ray luminosity. The X-ray luminosity shows a wide spectrum of variability time scales from the 15 minute pulsations to several days. It is not known whether the long term changes are periodic and thus helpful in determining the orbital parameters, or whether they reflect changes or inhomogeneity in the mass-loss of the Be star.

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FIGURE CAPTIONS

Figure 1 - Raw MPC (1.5-10 KeV) light curve from day 382.87 to 383.37 of 1978 (JD 2443891). The intensity scale is given in MPC counts/2.56 sec (1 MPC ct $s^{-1} \approx 1.6 \times 10^{-11}$ erg cm^{-2} s^{-1}. The arrows point to the expected positions of maxima according to the 14.9 minute period and are labeled with the corresponding cycle number. a,b,c,d are intervals referred to in Figure 3.

Figure 2 - Fourier transform of the MPC data for periods longer than 2 minutes.

Figure 3 - Pulse profiles obtained by folding the 3-10 keV MPC data with P = 893.8 seconds and initial (arbitrary) epoch at Day 382.87, 1978. a) first outburst, b) second outburst, c) prior to the first outburst and d) between outbursts.

Figure 4 - a) Pulse profile from the entire, folded data set in Figure 1.
b) Hardness ratio.

Figure 5 - Light curves during the OSO-8 observation and the HEAO-1 A2 scan. For the OSO-8 intensities 1 count/s is approximately 1 μJy. This corresponds approximately to 0.0025 cts cm^{-2} s^{-1} for the HEAO-1 A2 rate combination used. The scales have been chosen so that they are approximately equivalent. The OSO-8 points are averages over ~ 2000 s, the A2 points over 0.1 day.

Figure 6 - Light curve for the HEAO-1 A2 pointed observation.

Figure 7 - Inferred incident spectra above 1.3 keV for all observations. The times covered in the MPC data include the intervals of SSS data, but are not identical. That the OSO-8 spectrum matches on to the MPC spectrum shown is presumably fortuitious, since both are averages over apparently random flares.

TABLE 1: SPECTRAL FITS

Detector		Thermal Brems[a]		Power Law[b]		F_X(2-10 keV)	L_X[d]
		kT(keV)	$N_H(10^{22}cm^{-2})$	α	$N_H(10^{22}cm^{-2})$	$(10^{-10}ergs\ cm^{-2}s^{-1})$	$(10^{34}\ ergs\ s^{-1})$
MPC	Flare	>25	4.5	1.2±0.1	3.2±1	3.6	22.9
(1.3-12 keV)	Low	>20	4.5	1.2±0.3	3.2±1	0.2	1.3
SSS	Flare	>10	3±2	1.0±0.5	2±1		
(1.3-4.5 keV)				1.2(Fixed)	1.6±0.2		
	Low	>10	3±1	0.7±0.1	0.3±0.2		
				1.2(Fixed)	0.5±0.2		
HEAO-1 A2	Low	14±9	3±2	1.8±0.2	5±2		
(2-20 keV)							
OSO-8	High	40±13	---	1.2(Fixed)[c]	---		
(10-60 keV)							

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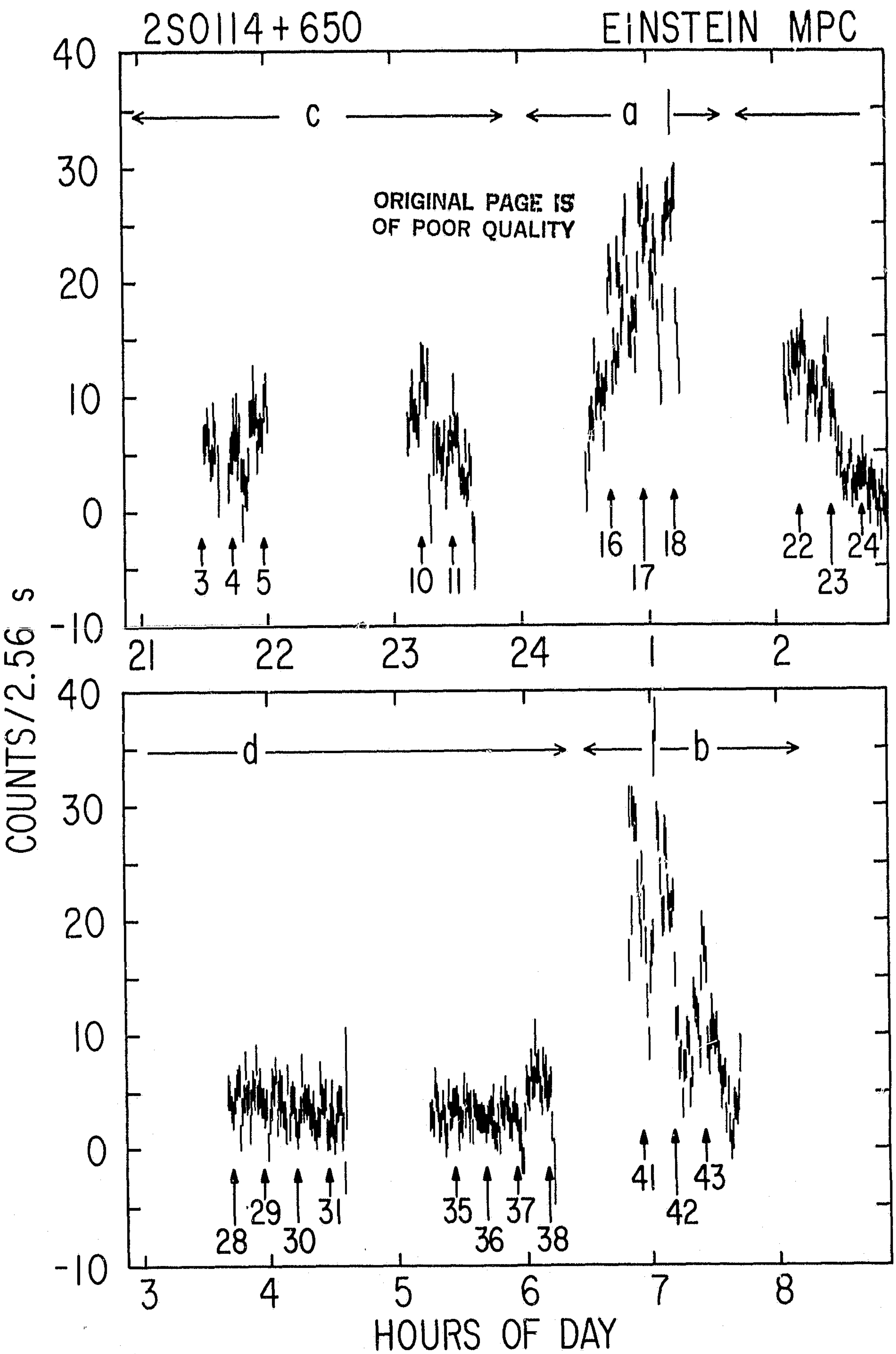
[a] $(dn/dE)_T = c\ g\ E^{-1}\ e^{-E/kT_e-N_H}\ \sigma(E)$, where g is the Gaunt factor. $\sigma(E)$ is the cross section for photoionization of cold gas (Fireman 1974).

[b] $(dn/dE)_p = cE^{-\alpha} e^{-N_H \sigma(E)}$

[c] $$dn/dE = (dn/dE)_p \times \begin{cases} 1 & \text{for } E < E_c \\ e^{-(E-E_c)/E_f} & \text{for } E > E_c \end{cases}$$

[d] Estimate of total luminosity assuming the spectrum c for the hard component with E_C and E_F from the OSO-8 results.



2S0114+650
EINSTEIN MPC
ORIGINAL PAGE IS
OF POOR QUALITY
c
a
b
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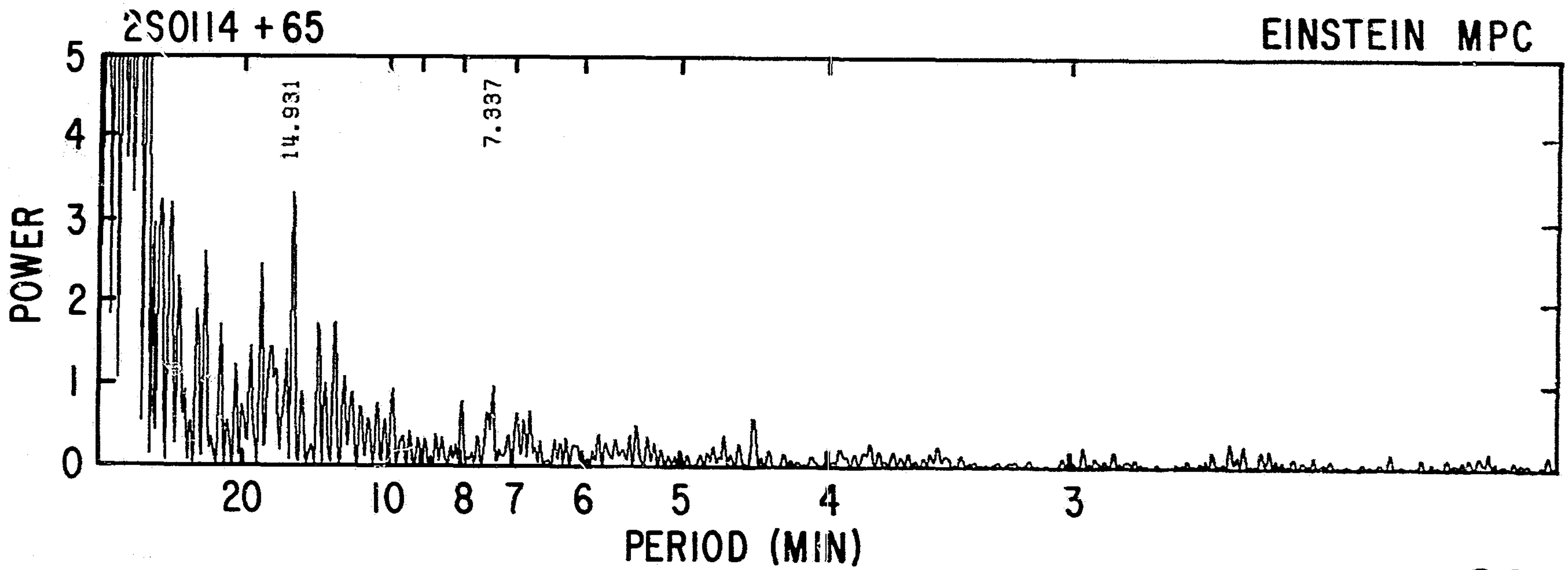
3 4 5 10 11 16 17 18 22 23 24
28 29 30 31 35 36 37 38 41 42 43
COUNTS/2.56 s
HOURS OF DAY



2S0114 + 65
EINSTEIN MPC
POWER
5
4
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1
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14.931
7.337
20
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PERIOD (MIN)

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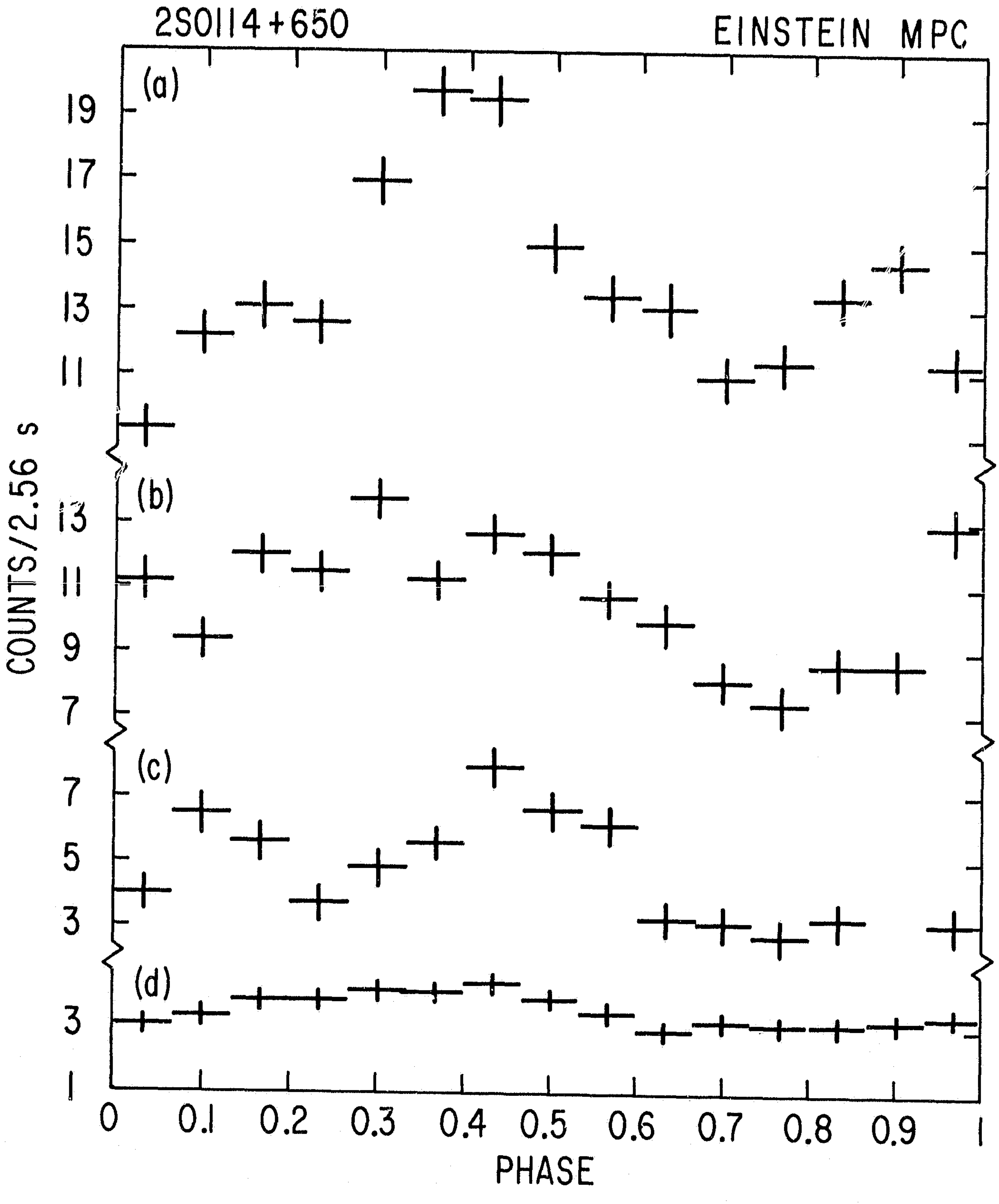
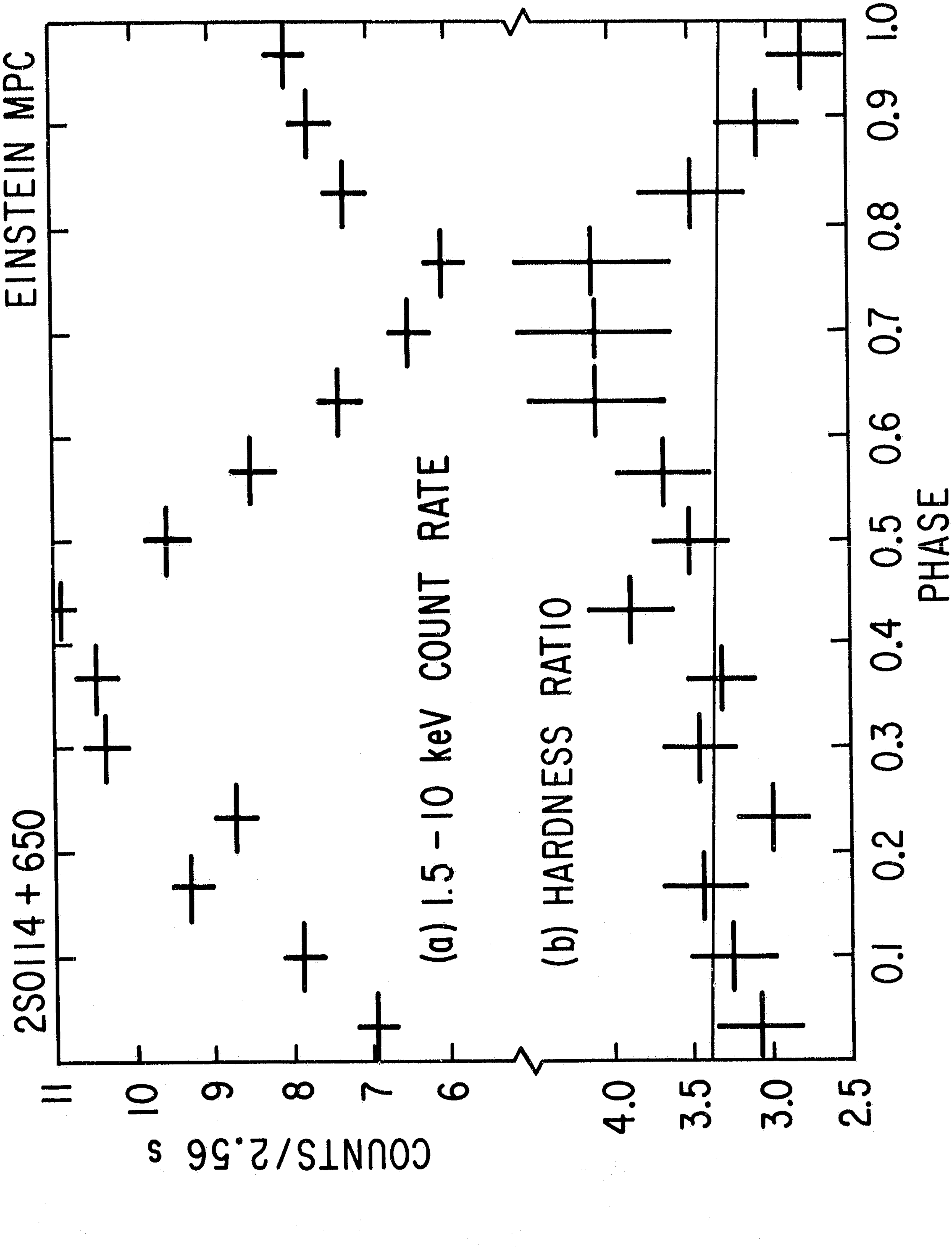
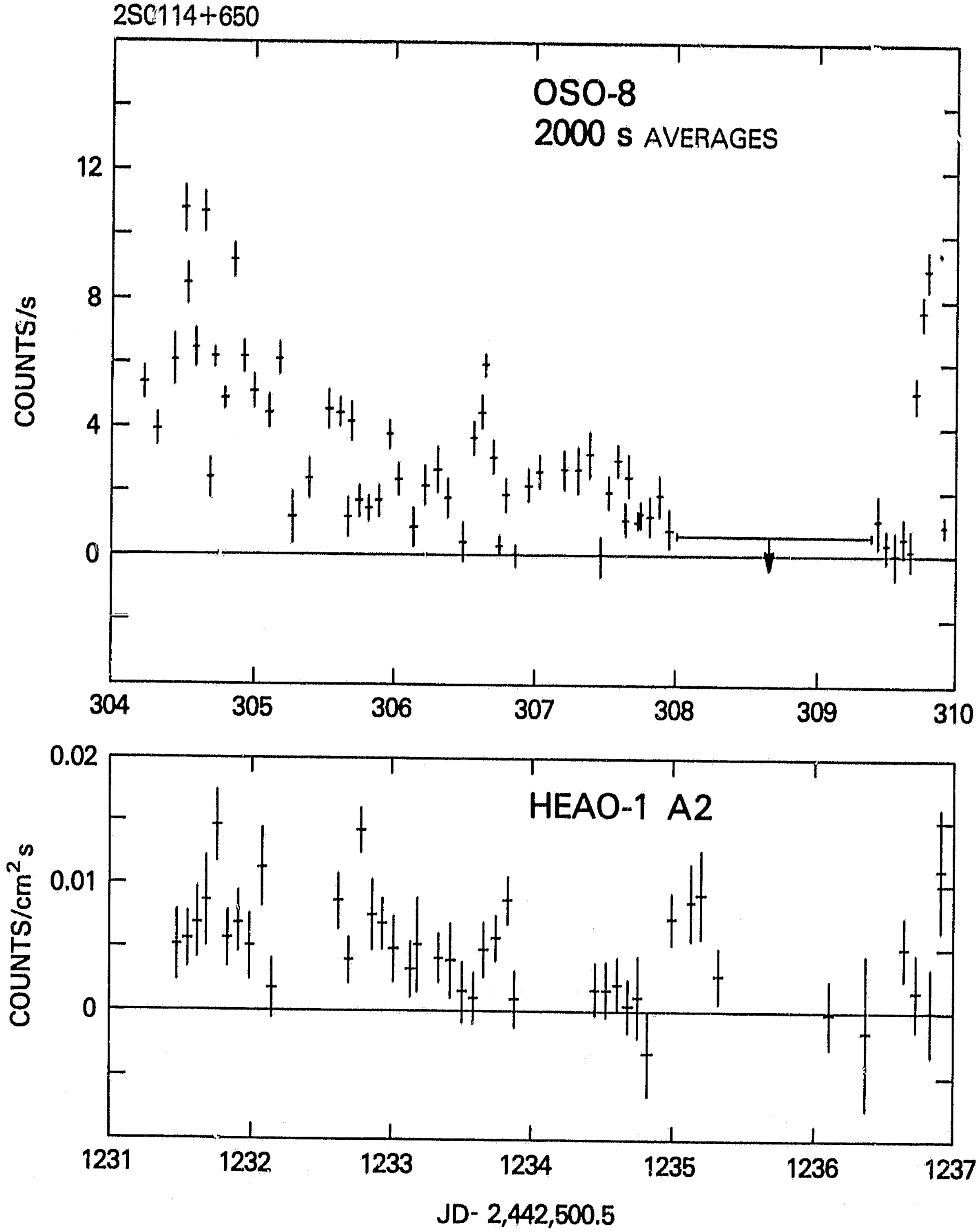
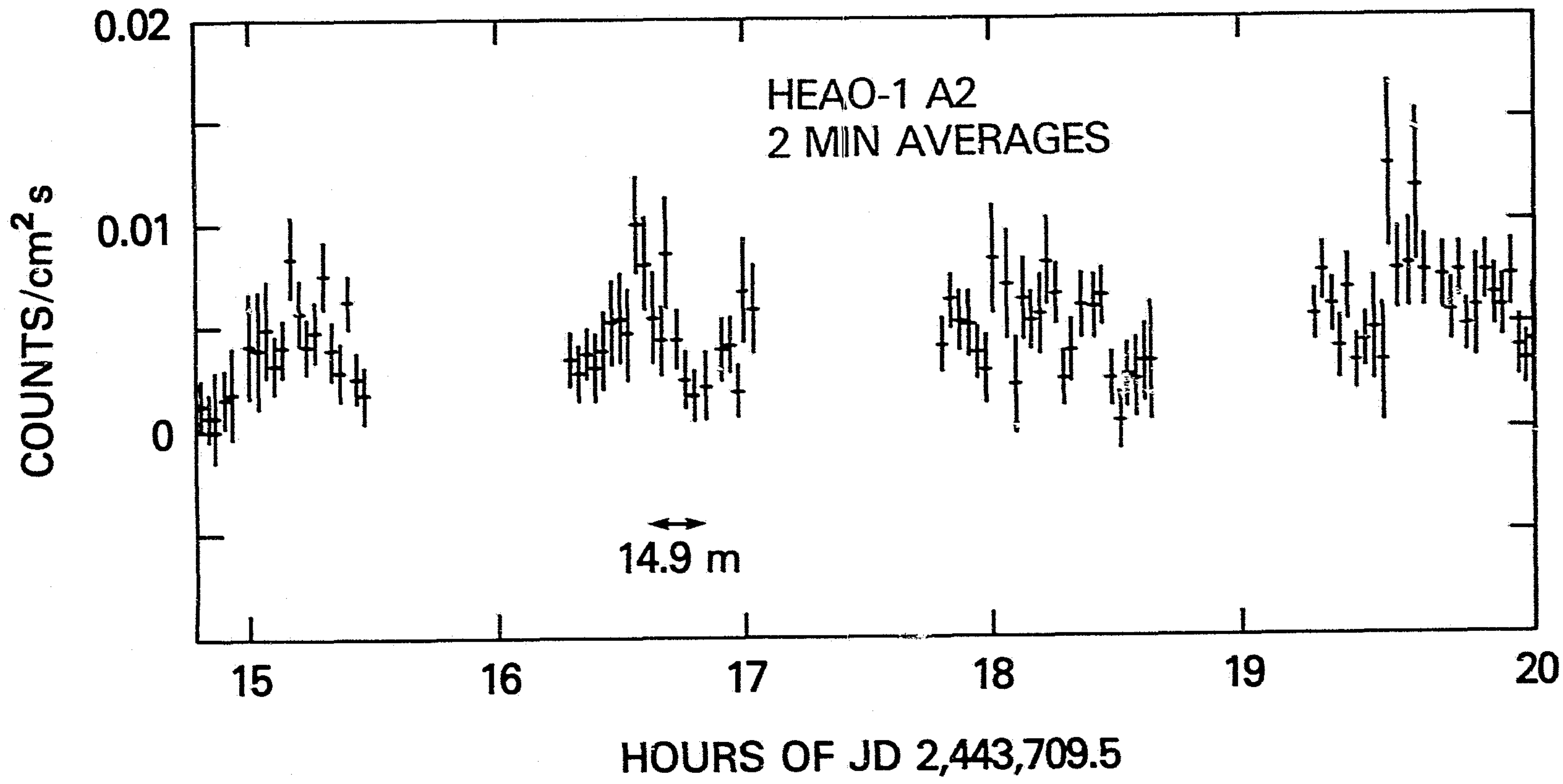
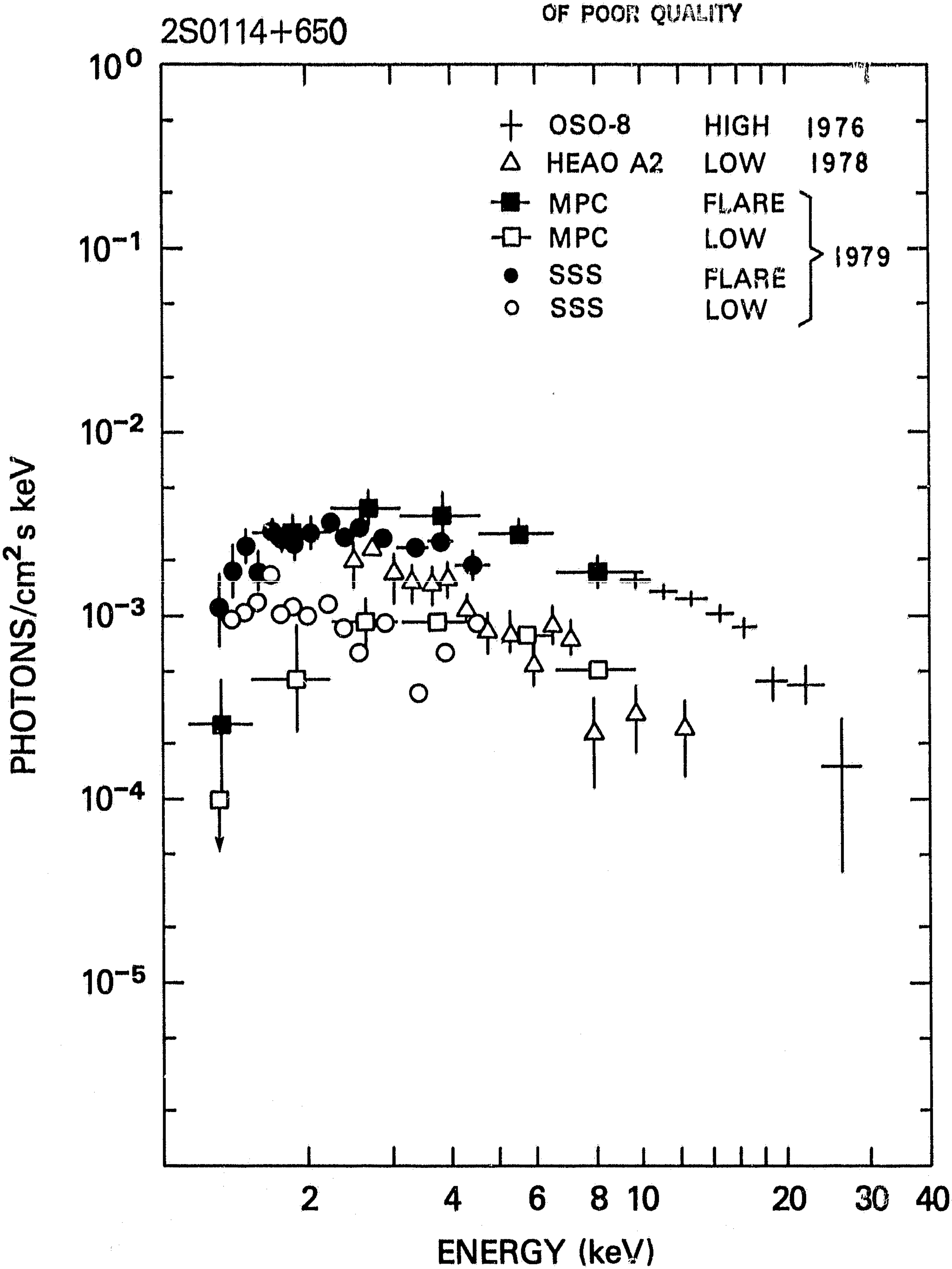



2S0114+650
EINSTEIN MPC
(a) 1.5 – 10 keV COUNT RATE
(b) HARDNESS RATIO
COUNTS/2.56 s
PHASE
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
11
10
9
8
7
6
4.0
3.5
3.0
2.5


2S0114+650
OSO-8
2000 s AVERAGES
COUNTS/s
12
8
4
0
304
305
306
307
308
309
310
HEAO-1 A2
COUNTS/cm²s
0.02
0.01
0
1231
1232
1233
1234
1235
1236
1237
JD- 2,442,500.5


0.02
0.01
0
COUNTS/cm²s
HEAO-1 A2
2 MIN AVERAGES
14.9 m
15
16
17
18
19
20
HOURS OF JD 2,443,709.5


2S0114+650
OSO-8 HIGH 1976
HEAO A2 LOW 1978
MPC FLARE
MPC LOW
SSS FLARE
SSS LOW
1979
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
PHOTONS/cm^2 s keV
2
4
6
8
10
20
30
40
ENERGY (keV)